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APPENDIX F

HAZARDS TO AIRCRAFT OVER EXPLOSIVE TEST SITES

This appendix assesses the probability of aircraft being damaged by flying into a piece of shrapnel thrown up from a cased explosion or by experiencing the shock wave from an explosion. To solve the shrapnel problem, one must look into the ballistics of shrapnel, estimate the probability of an aircraft being in the volume of space where pieces of shrapnel might be while they are still in flight, estimate the probability of the lookouts not seeing such an aircraft in time to delay the explosion, and estimate the probability of the aircraft actually flying into one of the pieces of shrapnel. To solve the shock wave problem, one must also estimate the radius of the hemisphere within which damaging overpressures may occur.

A worst-case explosion would be 10,500 lb. TNT equivalent of slurry explosives in a case 3/8-inch (1 cm) thick. (Such a case would actually be cylindrical in shape, but the estimation of probabilities is easier and little different if the case is assumed to be spherical.) The radius of the spherical case would be 35 inches and its volume 105 cubic feet; the case would weigh about 1600 lb. Thus from a case weighing about a sixth as much as the explosive, fragments might attain velocities as high as 8000 ft/sec (2400 m/s) (Gurney formula, 1943).*

Next, we need an estimate of the number of fragments the explosive case will break into as a result of the explosion. Experience indicates that such a fragment might be as big as a foot in size, which is to say it might have a volume of 0.031 ft^3. We assume that the smallest fragment that can seriously damage an aircraft is about an inch in size (1 in^3 or 0.00058 ft^3 in volume.) Then, knowing that there will be more small than large fragments, we approximate this by a particle diameter distribution varying as r^{-n}, where n is between 2 and 3. (Such a distribution approximates the more usual log-normal distribution, and is easier to handle analytically. The form and the exponent are suggested by studies of particle sizes in radioactive fallout (Russell, 1966), but the answers derived by using them are only weakly dependent on the exact value of the exponent.) Then the mean fragment volume will be 0.0043 ft^3, and there will be about 780 fragments in the size range of concern.

Next, we must discuss the ballistics in air of case fragments. The problem has been extensively studied by Bishop (1958), and for the most part this discussion follows his analysis. Bishop's primary assumptions were a constant drag coefficient and an air density that does not vary with altitude. He also

* The usual formula for horizontal missile radius is $600W^{1/3}$; it is clear that this present analysis is inconsistent with that formula, for it predicts initial velocities that do not depend on charge weight, but only the ratio of case and charge weights. Apparently the usual formula is an empirical one based on small-charge experience.

took into account tumbling particles. The drag coefficient of an irregular-shaped particle does vary with its speed relative to the air, especially near Mach 1, but generally by no more than a factor of two. Air density varies with altitude, but very little for the altitude range of interest here. Tumbling particles he found to travel up to 50% farther than non-tumbling particles.

The deceleration of a fragment going vertically upwards is:

$$dv/dt = -g - kv^2,$$

where $k = \frac{1}{2}(\rho_a/\rho_m)(C_d/\theta)$ and involves the air drag parameters of drag coefficient (C_d), thickness of fragment (θ), and the densities of the fragment (ρ_m) and of the air (ρ_a). The solution of this differential equation is the substitution of the velocity-time relationship:

$$v = \frac{v_o - \sqrt{g/k}\ \tan(\sqrt{gk}\ t)}{1 + \sqrt{k/g}\ v_o\ \tan(\sqrt{gk}\ t)}$$

into the height-velocity relationship:

$$s = \frac{1}{2k} \ln \left(\frac{1 + kv_o^2/g}{1 + k\,v^2/g}\right),$$

where v_o is the initial velocity upwards. Similarly for a fragment falling, its acceleration downwards is:

$$dv/dt = -g + kv^2,$$

whose solution is:

$$s = s_o - \frac{1}{2k} \ln \left(\frac{(1 + e^{2\sqrt{kg}\ t})^2}{4\ e^{2\sqrt{kg}\ t}}\right)$$

where s_o is the altitude from which the fall starts, and t is measured from the start of fall.

In Figure 37 we present results calculated for both a one-inch and a one-centimeter thick particle, with an initial upwards velocity of 3000 m/s, a drag coefficient of 1, a metal density of 7.8 (steel), and an air density of .9 g/l. It appears that an inch-thick piece of shrapnel may reach a height of 1650 m (5400 ft) above its starting point and be in flight for about 40 seconds. A centimeter-thick piece of shrapnel may reach a height of 740 m (2400 ft) above its starting point and be in flight for about 27 seconds.

The horizontal analysis is a good deal more complicated; suffice it to say that a horizontal range of 4000 ft is possible, and that the initial part of the trajectory (until a fragment loses the bulk of its kinetic energy) is in almost a straight line from the explosion.

The Lurance Canyon Test Site is 58,000 feet (11 miles) from the middle of the Albuquerque International Airport and is near

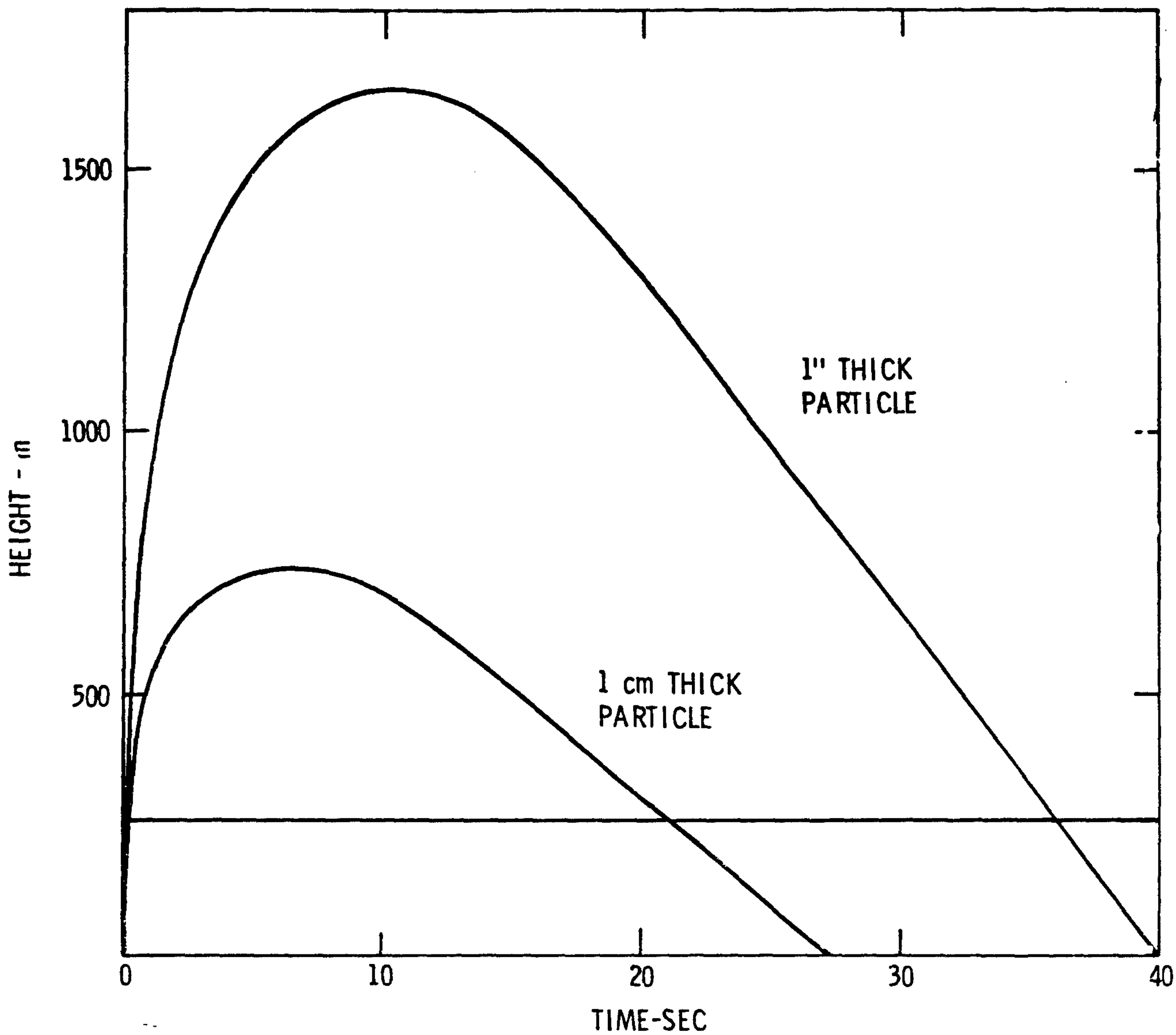

Figure 37. Height versus time calculations of shrapnel generated by cased explosion

frequently used landing and take-off patterns. There are on the average 574 departures a day at this airport, which is equivalent to about 420,000 take-offs and landings per year (FAA, 1974). The test site is at the bottom of a canyon with mountains around it on all sides but the west. Some of the peaks about are as much as 1200 feet higher than the test site, but more typically they are 850 feet higher and 2100 feet away.

Fragments from a cased explosion will fly in all directions, including into the ground. Since their trajectories must be at angles of greater than $\tan^{-1}(850/2100) = 22^{o}$ above the horizon to clear the adjacent mountains, the probability that a fragment escapes impacting the ground or the mountain is:

$$P_1 = (1 - \cos \theta)/2 = 0.31$$

where θ is the vertical angle, 68^{o}.

To estimate the probability that an aircraft will be in the area where pieces of shrapnel might be, while they are still in flight, we first estimate the area density of airplanes:

$$\rho_a = n/2\ vR,$$

where n is the number of planes taking off and landing at the airport per unit time (574 per day = 0.0133 per second, if all the traffic is in daylight hours); v is the aircraft velocity; and R is the distance from the airport. This assumes that all directions of approach (or leaving) the airport are equally likely, whereas experience indicates that planes coming from or leaving to the east prefer to turn short of the mountains.

Continuing, we are concerned with there possibly being a plane in a position to move into the danger zone while the case fragments are in flight, or for a time (T) of about 20 seconds (from Figure 37 this is the time a centimeter-thick particle will be above the level of the surrounding mountains). These will be planes in an area A = v D T, where D is the width of the danger zone, 8000 ft. Thus the probability of an aircraft coming into the danger zone is, apart from other considerations:

$$P_2 = \rho_a A = (n\ D\ T)/(2\ \pi\ R) = 0.0058 \text{ per test}$$

The probability that an aircraft will not be detected by the lookouts in a tower on an adjacent ridge will be assumed to be one in a hundred:

$$P_3 = 0.01$$

Finally we need the probability that, even if an aircraft should get by the lookout and fly into the missile hazard zone, the paths of a piece of shrapnel and of the aircraft would intersect. Generally speaking, the pieces of shrapnel are near the tops of their trajectories and moving much more slowly than the aircraft, so they will be treated as stationary, and the air-

craft moving. The number of fragments has been determined to be about 780. The number density of fragments is:

$$\rho_f = N/V_{total}$$

and the volume swept out by an aircraft traversing the hazard zone will be:

$$V = A_{ac}\overline{d},$$

where $\overline{d}$ is the average distance traveled by an aircraft in the danger zone while the pieces of shrapnel are still in the danger zone. A detailed estimate, not repeated here, indicates that since an aircraft does not necessarily cross the danger zone at its point of greatest width and since it does not necessarily get all the way across the danger zone during the time pieces of shrapnel are in flight, the average distance travelled, $\overline{d}$, is about equal to the radius, r, of the danger zone, 4000 feet. Finally the volume of the danger zone is $\pi r^2 H$. The total probability is found to be:

$$P_4 = N\ A_{ac} r/\pi r^2 H = 0.0040,$$

where the vulnerable area A_{ac} has been taken to be 100 ft^2, and the height of the danger zone (H) 2400-850 = 1550 feet.

Two other factors act to reduce further the probability of damage to an over-flying aircraft, but are not evaluated here for lack of the necessary inputs. First, an aircraft has to be flying low, not more than 1500 feet over the terrain, and not all will fly that low. Second, the pieces of shrapnel do not all have the same velocity initially. A maximum velocity was used herein; if a velocity distribution with this as a maximum were used, one would find a lower density of pieces of shrapnel in the upper parts of the danger zone.

Finally, the joint probability per test of an aircraft being hit with a piece of shrapnel is the product of the foregoing probabilities, or:

$$P = P_1 P_2 P_3 P_4 = 7.2 \times 10^{-8} \text{ per test,}$$

or, since there have in recent years been an average of 41 tests a year conducted at this site, the probability (P) of a shrapnel-caused accident per year is

$$P = 2.9 \times 10^{-6}.$$

Turning now to the possible effects of the shockwave from an explosion on a low over-flying aircraft, we note first that ordinary aircraft are considered endangered by a passing shock wave if the shock overpressure exceeds 0.5 psi. Pressures this large or larger are felt everywhere within a hemisphere of radius 1650 feet from a 10,500 lb. surface burst. Although this dis-

tance is smaller than the range of pieces of shrapnel used above, there is no possibility of an aircraft not flying into the shock wave if it is close enough. An aircraft cannot, so to speak, fly between the pieces of shrapnel. Thus $P_1 = P_4 = 1$.

The portion of the 1650-foot radius hemisphere above the 850-foot level of the surrounding hills has a radius of 1400 feet. The danger period is also smaller, and will be taken as the time necessary for the shock wave to travel from the level of the tops of the hills to the 0.5-psi radius, a distance of 800 feet taking a time of 0.8 second. Then, using the previous formula,

$$P_2 = (.0133 \times 2800 \times .8)/(6.28 \times 58000) = 8.2 \times 10^{-5}.$$

As before,

$$P_3 = 0.01$$

Thus the joint probability per test of overpressure damage to a low over-flying aircraft is:

$$P = P_2 P_3 = 8.2 \times 10^{-7} \text{ per test}$$

or since there are 41 such tests a year,

$$P = 3.4 \times 10^{-5} \text{ per year.}$$

The unevaluated factor of aircraft altitude is obviously even more telling with respect to overpressure damage than for shrapnel damage.